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## **Modeling Wireless Signal Transmission Performance Path Loss for ZigBee Communication Protocol in Residential Houses**

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**Abstract.** *Low-cost and high performance wireless technologies make it a reality to develop a wireless HVAC control system for multi-zone environmental control in residential houses to improve individual comfort and reduce energy consumption. The lack of understanding on signal transmission performance of wireless sensor network in residential houses limited the application of wireless sensor networks, especially the new ZigBee protocol. This paper is to establish path loss models for predicting wireless data transmission performance in residential houses for ZigBee protocol. Factors affecting the wireless data transmission in residential indoor environment include free space separation, walls, floors, and wireless device interference. Effects of these factors on the path loss in residential indoor environment were evaluated through empirical testing using received signal strength indicator (RSSI) value measured by commercial ZigBee modules and an embedded microcontroller-based data acquisition system. The model for the effects of walls on the same floor was able to predict 73.6% of the system variability. The measured RSSI data were made versus*

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*1mW transmission source and therefore the RSSI-based path loss models were able to accurately predict the performance of wireless signal of stronger or weaker power transmission systems.*

**Keywords.** HVAC control, wireless sensor network, Zigbee, path loss.

## Introduction

HVAC (heating, ventilating, and air conditioning) system is commonly used to ensure indoor occupants' thermal comfort, preserve indoor air quality and optimize energy consumption of buildings (Nassif et al., 2008). Energy use of a HVAC system accounts for 28% of total energy consumed in commercial buildings and 43% in residential homes (Wang et al., 2006). Currently, residential houses typically have one set of HVAC system and a whole house is controlled as one-zone. One-zone HVAC control system has difficulty to meet various comfort requirements and is not energy efficient (Wang et al., 2003). Multi-zone HVAC control systems can meet different thermal comfort requirements better and are more energy efficient than one-zone HVAC control systems (Mcdowall, 2007), but are complicated with more sensors and wires. It is costly to run wires in newly built houses for multi-zone HVAC control and even more expensive to retrofit HVAC control systems from one-zone to multi-zone systems in existing houses. It has been estimated that the typical wiring cost in industrial installations is \$130-160 per meter while wireless technologies can eliminate 20-80% of this cost (Wang et al., 2006). Therefore, wireless technologies make it a reality to develop a multi-zone wireless HVAC control system for residential houses to improve individual comfort and reduce energy consumption.

Currently, the state-of-the-art wireless HVAC control technology is to embed sensors into microcontroller-based RF (radio frequency) wireless transmitter and receiver systems, and integrate the wireless transceiver system with either an existing HVAC control system or a PC or a PDA(Personal Digital Assistant) based monitoring and control system. Typical wireless sensors include temperature sensors, humidity sensors, CO<sub>2</sub> sensors, flying dust sensors, light sensors, energy meters and video cameras (Chung et al., 2005; Jang et al., 2008). A wireless sensor unit is the essential component of a whole wireless sensor network (Jang et al., 2008). The primary difference among all the wireless sensor units is RF devices and their communication range, reliability, data rate, and cost. It was indicated that the transmission reliability of wireless sensor networks was not fully understood and proven for process control (Wang et al., 2006). Chung et al. (2005) used 433.92 MHz RF modules with one-way transmission (transmitter to receiver) in the design of a wireless monitoring system for room environment. The maximum effective transmission range was 10 m where 99% reliability was guaranteed although the data sheet shows the transmission range is up to 75m in a building and 300m on open ground. The transmission distance can be greatly extended by using repeaters between 900 MHz transmitters and receivers in the wireless HVAC control system (Kintner-meyer and Brambley., 2006). Control actions can be introduced by integrating a wireless sensor network with an existing HVAC control network via translators. But the repeaters and translators significantly increased the cost. The high cost has been a primary factor that limited the wide application of wireless sensor networks.

The emergence of the low-cost and mesh-route supportive wireless protocols, ZigBee (IEEE802.15.4, 2.4GHz), can reduce the cost of monitoring and controlling indoor environment using wireless systems while improve the reliability of the communication (Osipov, 2008). Molina-Garcia et al. (2007) demonstrated a wireless heating and cooling load monitor and control system using ZigBee standards and found that although minor, the communication performance was affected by wireless noises. Raimo (2006) showed three case studies of wireless mesh network for building HVAC control systems and indicated that research work was needed to reveal the performance of wireless signal transmission inside buildings. It is clear that ZigBee is a very popular and promising protocol for building control. However, the lack of the understanding on the performance of the ZigBee in residential houses limited its application.

Path loss prediction models are fundamental and widely-used tools to predict wireless signal attenuation for evaluation of wireless signal transmission performance (Lott and Forkel, 2001; Ghassemzadeh and Tarokh, 2003; Ghassemzadeh et al., 2002; Cheung et al., 1998; Panjwani et al., 1996; Andersen et al., 1995; Seidel and Rappaport, 1992). Seidel and Rappaport (1992) developed distance dependent path loss models for wireless communications at 914MHz in multifloored buildings. Path loss models for radio frequencies 900 MHz, 1300 MHz, 1500 MHz, 1900 MHz, and 4000 MHz were developed by Andersen et al. (1995). A multi-wall-and-floor path loss model for 5GHz was developed by considering the materials of walls and floors (Lott and Forkel, 2001). The above research works mainly focused on commercial buildings. Path loss models in terms of LOS (line-of-sight) and NLOS (Non-line-of-sight) transmission at 5GHz within residential homes were developed by Ghassemzadeh and Tarokh (2003). However, the path loss models for 2.4GHz, which is the frequency that ZigBee operates at, in residential homes, do not exist. Liechty et al. (2007) demonstrated the empirical path loss model for 2.4GHz in outdoor environment based on Seidel-Rappaport path loss model. Lymberopoulos et al. (2006) demonstrated the characteristics of radio signal strength variability in indoor environment (basketball court and testbed) using ZigBee (2.4GHz) wireless transceivers. The main finding was that antenna orientation greatly affected the signal transmission. A path loss model was developed to predict the signal transmission performance of ZigBee wireless sensor network in poultry layer facilities (Darr and Zhao, 2008). However, No literature revealed the full performance of radio signal strength attenuation of ZigBee in residential home environment.

The objective of this work was to quantify the electromagnetic performance of ZigBee wireless sensor network within a residential house environment and derive the parameters of Seidel-Rappaport path loss models to predict the signal attenuation to better position wireless sensors.

Specific objectives include:

- Evaluate effects of key factors that cause wireless path loss within a residential house environment;
- Develop a path loss model to predict 2.4GHz wireless signal transmission in a residential house environment;
- Validate the model by direct measurement.

## **Background**

### ***Theoretical Analysis of Path Loss Models***

Radio wave propagation occurs when wireless signal transmits in the air. The signal strength will be attenuated by many mechanisms due to reflection, diffraction, and scattering (Figure 1), which are the three basic mechanisms that affect the propagation in a wireless communication system (Rappaport, 2002).

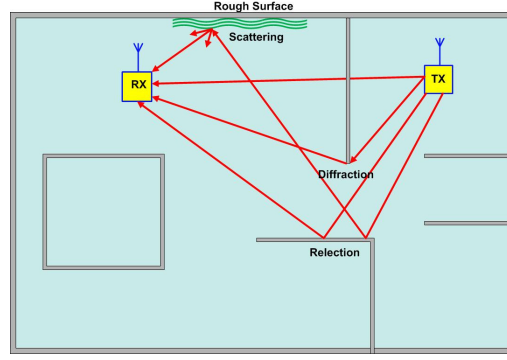


Figure 1. Wireless Signal Attenuation Due to Reflection, Diffraction, and Scattering.

Path loss, defined as the difference between the transmitted power and the received power, is widely used to predict the signal attenuation. The fundamental model for the predication of the path loss in free space where the transmitting and receiving antennas are separated within open space, which is also defined as LOS, is Friis free space equation (equation 1) (Rappaport, 2002).

$$P_r(d) = \frac{P_t G_r G_t \lambda^2}{(4\pi d)^2 L} \quad (1)$$

Where:  $P_r(d)$  = Power received (dB);  
 $P_t$  = Power transmitted (dB);  
 $G_r$  = Receiver antenna gain (unitless);  
 $G_t$  = Transmitter antenna gain (unitless);  
 $\lambda$  = Wavelength (m);  
 $d$  = T-R(transmitter-receiver) separation distnace(m);  
 $L$  = System loss factor (unitless).

$L$  represents the miscellaneous losses due to the hardware of the communication system. A value of 1 means that there is no loss from the hardware of the communication. Assume  $L$  was equal to 1 for the discussions in this paper. This assumption was reasonable since the cable loss of the ZigBee module used in this test was only 0.2dB (Digi Datasheets). Another common form of this power equation is expressed by the ratio of power received to power transmitted (equation 2).

$$PL (dB) = 10 \log_{10} \frac{P_r}{P_t} = 10 \log_{10} \left[ \frac{G_t G_r \lambda^2}{(4\pi d)^2} \right] = 10 \log_{10} \left[ \frac{G_t G_r \lambda^2}{(4\pi)^2} \right] - 20 \log_{10} (d) \quad (2)$$

The first term is based only on antenna gains and signal wavelength. This is a constant for a particular wireless link and independent of environmental factors. The second term depends on the transmission distance between a transmitter and a receiver.

A common way to predict path loss is to use empirical models. A parameter of  $n$ , which is defined as path loss exponent, is used to denote the relationship between the path loss and communication distance as equation 3 showed (Ghassemzadeh et al., 2002).

$$PL (dB) = PL (d_0) + 10 n \log_{10} \frac{d}{d_0} + X_\sigma \quad (3)$$

The first term is the path loss at a known close-in reference distance  $d_0$ , which is usually 1 m for indoor environment.  $X_\sigma$  represents a normal random variable in dB associated with the standard deviation of  $\sigma$  dB. The smaller the value of  $X_\sigma$ , the more accurate the path loss model is. The value of  $n$  is known to be 2 for LOS path in free space. Typical values of  $n$  and  $X_\sigma$  for different communication frequencies in various environments can be found from (Andersen et al., 1995). When considering the obstructions between transmitter and receiver, the model (3) can be modified as equation 4 showed (Liechty et al., 2007).  $OBS_i$  is the number of the obstructions of type  $i$  and  $AF_i$  is the attenuation factor for the obstructions of type  $i$ .

$$PL(dB) = PL(d_0) + 10n \log_{10} \frac{d}{d_0} + \sum_i OBS_i \times AF_i + X_\sigma \quad (4)$$

It turned out that the path loss between floors does not increase linearly in dB as transmission distance increases linearly (Andersen et al., 1995). It is necessary to add a floor-attenuation-factor (FAF) (Panjwani et al., 1996). Therefore, the overall indoor path loss model is given by

$$PL(dB) = PL(d_0) + 10n \log_{10} \frac{d}{d_0} + \sum_i OBS_i \times AF_i + FAF + X_\sigma \quad (5)$$

If the factors such as  $n$ ,  $AF_i$ ,  $PL(d_0)$  and  $FAF$  are accurately known, they can be used to predict path loss of wireless signal attenuation through residential house environment. Based on this model, this work was to find the values of all these factors for ZigBee wireless protocol in residential house environment.

RSSI (received signal strength indication) was brought into much attention recently as a significant means to contribute to the establishment of wireless signal attenuation models because it eliminates the need for additional hardware on small wireless devices and model results based on RSSI provide high comparability among different wireless networks since RSSI is relative to 1 mW transmission source (Darr and Zhao, 2008; Liechty et al., 2007; Lymberopoulos et al., 2006). Therefore, the predicted models were derived by collecting and analyzing raw RSSI data in this paper.

## Materials and Methods

### Design of Wireless Test Devices

In order to experimentally quantify the path losses of wireless signal within a residential house environment, a test fixture was designed by incorporating a ZigBee module (XBee ZNet 2.5, Digi, Minnetonka, MN) with the power conditioning and microcontroller-driven data acquisition circuits. This ZigBee module was selected for the test because it provides easy serial communication interface with microcontrollers, has multiple controlled transmission power outputs (adjustable from -8 dBm to +4 dBm), and consumes low power (up to 35 mA for transmission and 38 mA for receiving if boost mode disabled while less than 1  $\mu$ A for power-down status). Additionally, the small size and the package of DIP (dual in-line package) made it easy to be embedded in custom designed circuit boards. In the test, the transmit power was chosen to be +4dBm, which was equivalent to 2.5 mW, for the optimal transmission performance. The standard omni-directional antenna used in the test provided the gain of 2.1dBi. The receiver sensitivity was -96 dBm. The functions and configurations of the XBee ZNet 2.5 module were set up through a series of AT serial commands.

A pair of custom designed test devices were used to contain ZigBee module embedded circuit boards to determine the wireless path loss (Figure 2). One served as the transmitter while the other one acted as the receiver. Both the transmitter and the receiver were mounted five feet high from the ground to simulate the typical installation height of HVAC sensors and control units. A microcontroller (PIC18F458, Microchip Technology Inc., Chandler, Arizona) was embedded in the transmitter board to control the wireless data transmission. A data logging board (Flash Core B, Tern, Inc., Davis, CA) was connected to the receiver module to acquire and store the data to a compact flash card. Although the ZigBee modules could produce mesh network, point-to-point communication was still selected to evaluate the performance of ZigBee for comparison with other wireless communication protocols. The microcontroller on the transmitter board initialized the transmission by sending a package data to the receiver via the ZigBee module. Once the receiver received the data, it sent the same data back to the transmitter for acknowledgement. Then after the transmitter received the acknowledgement, the “AT+DB” command from the ZigBee module reported the RSSI value of this link to the microcontroller. The microcontroller sent the RSSI value to the receiver through the ZigBee module for storage. Then the same procedure was repeated and the transmitter sent the RSSI values to the receiver at 0.5 Hz.

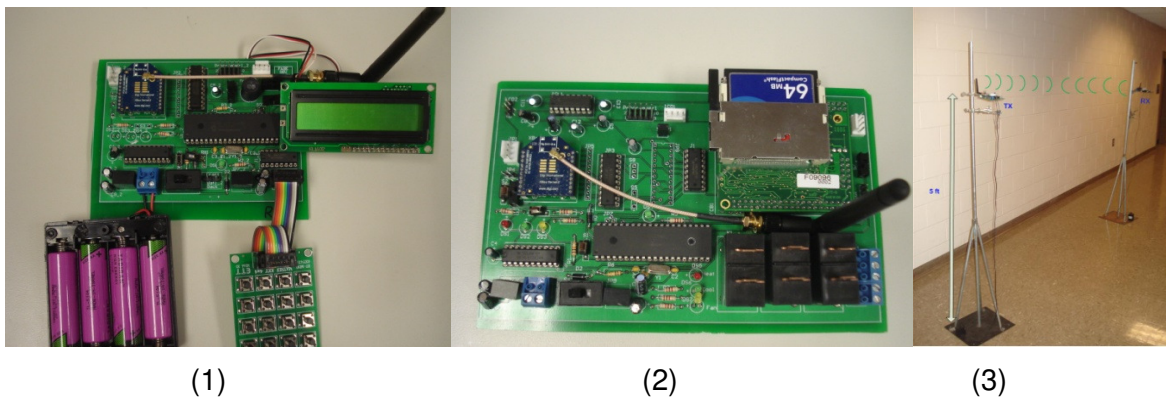


Figure 2. (1): Transmitter Circuit Board with XBee ZNet2.5 ZigBee Module Mounted; (2): Receiver Circuit Board and (3): Custom Designed Test Devices with Circuit Boards Mounted.

### ***Test Facility Selection***

Four typical two-story houses were selected as the test facilities. They have the size of approximately 50 feet times 30 feet on each floor of each house. The height of rooms is 8 to 9 feet. The house walls are all wood structures of 2×4 inch frame with dry-walls. The house floors are also wood structures with either carpets or wood floors. HVAC ducts were installed underneath the first floor and above ceiling in the attics. These four residential houses were located in Dublin, OH and all of them had similar structure and layouts (Figure 3). However, house 2 was a little different from other three houses since a mezzanine was between the first floor and the second floor. Therefore, house 1, 2 and 3 were used to conduct experimental tests for development of the models to reduce the potential variation of the experimental data due to the special structure of house 2 while the house 4 was used to validate the model.



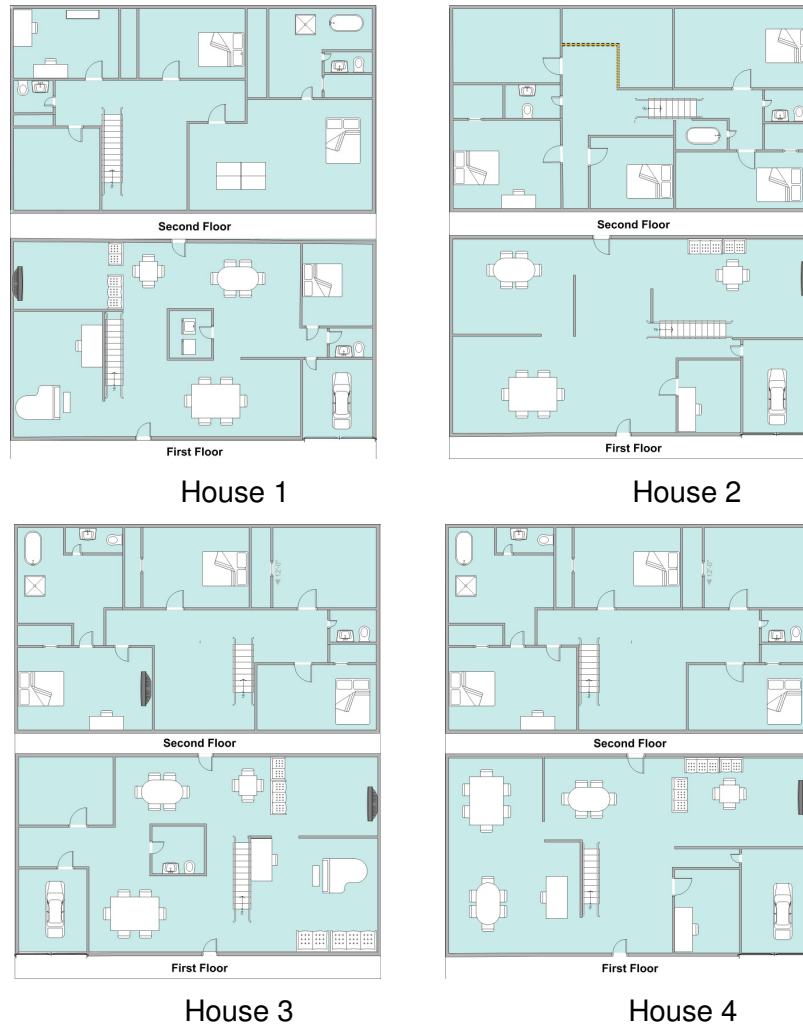


Figure 3. The Floor Layouts of Four Typical Residential Houses Used for the Tests.

### ***Experimental Plan and Statistical Analysis***

Measurements were made within open space and non-open space of the homes. The factors that affect the wireless signal transmission including transmission distance, wall separation, floor separation, and wireless device interference were examined using a factorial-randomized complete block design.

#### ***Single Floor Attenuation***

Table 1 showed the experimental test locations for testing the effects of walls and indoor open space on a single floor. The value of 0 for the number of walls represented open space. An example of the sensor locations was shown on Figure 4 (1). Although some furniture was between the transmitter and the receiver in the same space, they were lower than the heights of the transmitter and the receiver, thus this could be still considered as open space. Transmission distances from 0 to 50 ft in the open space of a typical residential house were tested. The transmission distances from 1 to 4 walls were determined for the same consideration.

Table 1. Experimental Path Loss Measurement Plan of Locations for Single Floor.

Number of Walls	Transmission Distances Tested (ft)					
0 (open space)	0.1	10	20	30	40	50
1	1	5	12	20		
2	4	9	14	19	23	
3	11	18	27			
4	28	33	37			

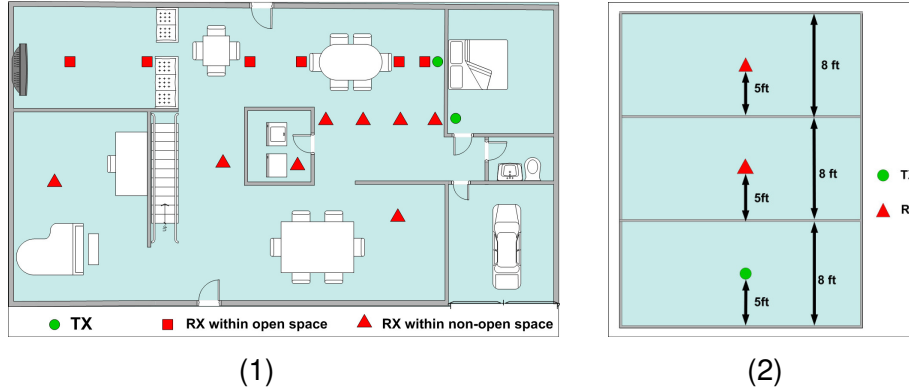


Figure 4. (1): An Example of the Sensor Locations within One Floor.  
(2): The Sensor Locations on Multiple Floors.

### ***Multi-Floor Attenuation***

The transmitter and the receiver were placed at the same height (5 feet) on each floor and separated by 0, 1, and 2 floors (Figure 4 (2)). Assume all the floors have the same typical height, which is 8 feet. Then the transmission distance will be  $8 \times \text{floors}$  (ft). The RSSI data for the link between the transmitter and receiver were measured and recorded.

### ***Wireless Device Interference***

ZigBee uses ISM (industrial, scientific and medical) 2.4GHz as its radio frequency which is also shared by Bluetooth, WiFi and 2.4GHz cordless phone. The operation band covered by ISM 2.4GHz is from 2.4GHz to 2.483GHz and is divided into different channels. In the reality, ZigBee, WiFi, Bluetooth and 2.4GHz cordless phone operate at different channels. The channel width for WiFi, Bluetooth and ZigBee are 22MHz, 1MHz, and 3MHz separately. ISM 2.4GHz band is broken down to 16 channels for ZigBee, 79 channels for Bluetooth and 11 channels for WiFi in North America (Woodings and Gerrior. 2006.). The layouts of channels for WiFi, Bluetooth and ZigBee were shown on Figure 5.

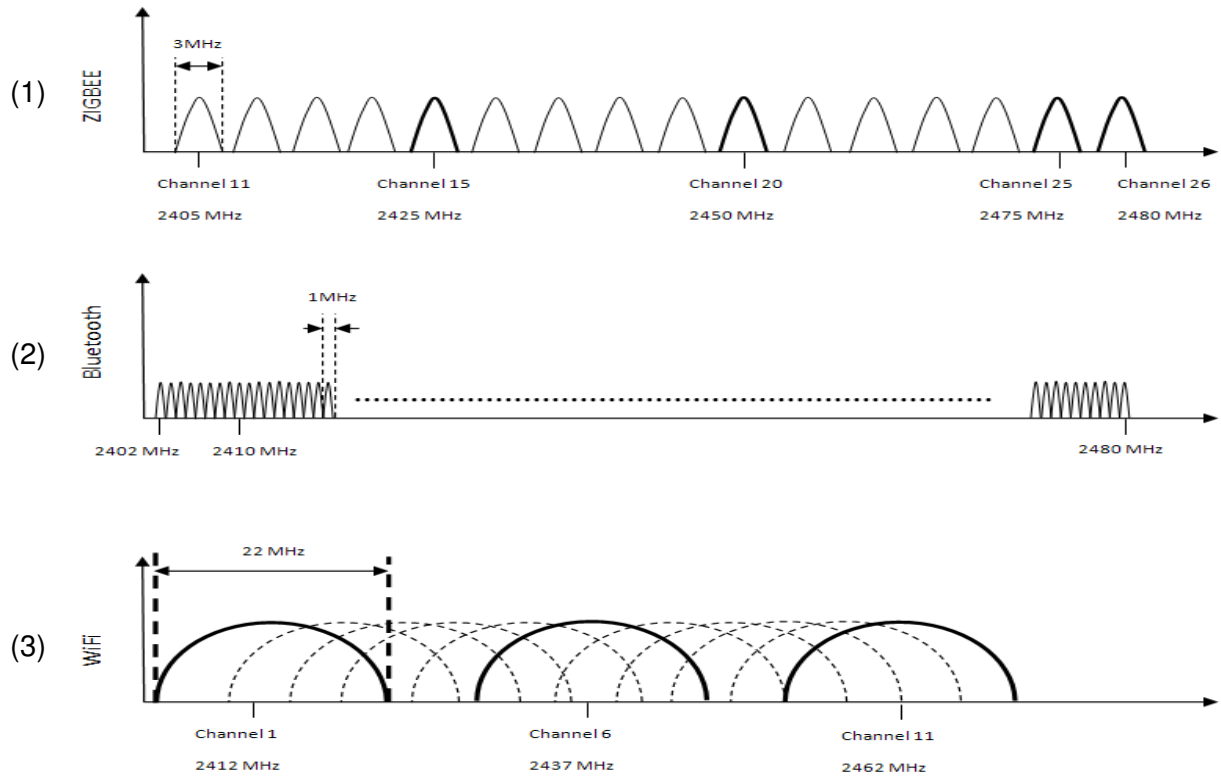


Figure 5. Channel Distributions of (1) ZigBee, (2) Bluetooth, and (3) WiFi Protocols in the ISM 2.4GHz Band.

There exist overlap among channels of ZigBee, Bluetooth, and Wi-Fi. Thus it is possible that the interference among different protocols could occur. However, the collision-avoidance algorithms were designed to deal with this issue. ZigBee and Wi-Fi search and find a quiet channel before they decide to start the transmission. Bluetooth hops among 79 channels to avoid the interference. Theoretically, the optimal solution for ZigBee is to use channel 15, 20, 25 or 26, which fall out of the often-used non-overlapping Wi-Fi channels 1, 6 and 11 (ZigBee Alliance, 2007). In each test residential house, one WiFi router that also supported a 2.4GHz cordless phone and several WiFi adapters, several Bluetooth devices, and one group of test ZigBee devices, were set up. The co-existence among ZigBee, Bluetooth, WiFi and cordless phone should not limit the applications. However, a test procedure was designed to explore the wireless data transmission performance in the scenarios where WiFi, Bluetooth and cordless phone co-existed with ZigBee.

RSSI was measured when all the wireless devices were present first and then absent between the transmitter and the receiver that were separated by two walls. Two-sample t-test was conducted to compare if other 2.4GHz wireless devices affected the ZigBee communication.

### **Statistical Analysis**

The experimental results were analyzed using Minitab (v15.1.1.0, Minitab, Inc., State College, Pa). The statistical significance was 0.05 for all the tests.

## ***Determination of Sample Size***

Due to the fast fading and variance of the path loss in houses with various layouts and structures, the sample size was designed to maintain the confidence interval within an acceptable level,  $\pm 1$ dB. RSSI data were continuously collected from the transmitter and reported to the receiver every two seconds in outdoor environment where no obstacles were around the transmitter and the receiver and thus could be as the simulation of free space. The transmitter and the receiver were placed 52 feet away from each other and 3000 data were collected. The statistical analysis for RSSI data in outdoor environment indicated that the mean value of RSSI was -72.501 dB and the standard deviation was 0.751 dB. Then the transmitter and the receiver were placed 52 feet apart in indoor environment where there were walls and furniture as obstacles between the transmitter and the receiver. 2994 data were collected and the statistical analysis showed that the mean RSSI was -80.602 dB and the standard deviation was increased to 1.787 dB. It was clear that the RSSI was reduced at the same distance in indoor environment in comparison with outdoor free space while the variance was increased, which indicated that the walls and furniture did contribute the efforts to path loss of the electromagnetic wave.

To ensure the accuracy of the sample size determination, the methodology to determine the sample based on the t-distribution is implemented using the equation 6, where  $S=1.787$ .

$$n = \left( \frac{t_{\alpha/2, df} \times S}{1} \right)^2 \quad (6)$$

The calculation trials based on t-distribution indicated that when  $n$  was equal to 15, the right part of equation 6 was most approximately equal to 15. Then at least 15 samples should be collected for each point where RSSI was measured. To ensure the factor of safety regarding the application of t-distribution, 60 was selected as the sample size.

## **Results and Discussions**

### ***Confirmation of Free Space Path Loss Model***

The Friis' free space path loss model was derived by the calculation of equation 2 based on the ZigBee operating frequency of 2.4GHz and the antenna gain of 2.1 dBi (equation 7), where  $d$  has the unit of feet.

$$PL(dB) = -25.53 - 20 \times \log_{10} d \quad (7)$$

The regression model of the path loss for free space from the experiment data was given by

$$PL(dB) = -44.37 - 18.40 \times \log_{10} d \quad (8)$$

A 73.8% difference in the offset evaluation and 8% difference in the slope evaluation were found between the empirical regression model and the theoretical model. It was indicated that there always existed errors between these two models (Figure 6), which could be explained by the fact that the real environment where the experiment was conducted was surrounded by trees, ground, grass and other objects instead of pure free space and these objectives could cause reflection, diffraction, and multipath error (Darr, 2007); however, the trend of the regression model was very close to the theoretical free space path loss model because two slopes were close to each other. It was clear that the errors decreased as the transmission distance increased but it stayed around 15 dB when the distance became large. Not only did

this coincide with the characteristics of the path loss change with logarithmic of the transmission distance but also validated the means to establish path loss models using RSSI.

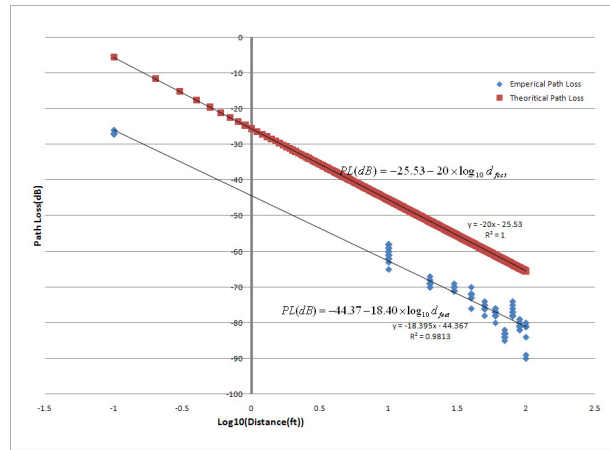


Figure 6. The Comparison between the Theoretical Free Space Path Loss Model and the Empirical Free Space Path Loss Model.

### ***Path Loss within Open Space of Residential Houses***

The results from the open space path loss within three houses were statistically similar at the 95% significance level (Figure 7(1)). The averaged regression model between the path loss and the logarithmic open space transmission distance yielded an offset of -51.39 dB and a slope of -14.01. This resulted in an n value of 1.4. An n value less than 2 indicated that less attenuation occurred in open space within a residential house than in open-air free space. The offset of -51.39 dB was close to the offset of the -44.37 dB in the empirical free space path loss model (equation 10). It also turned out that the house open space path loss acted very similar to that in open-air environment (Figure 7(2)).

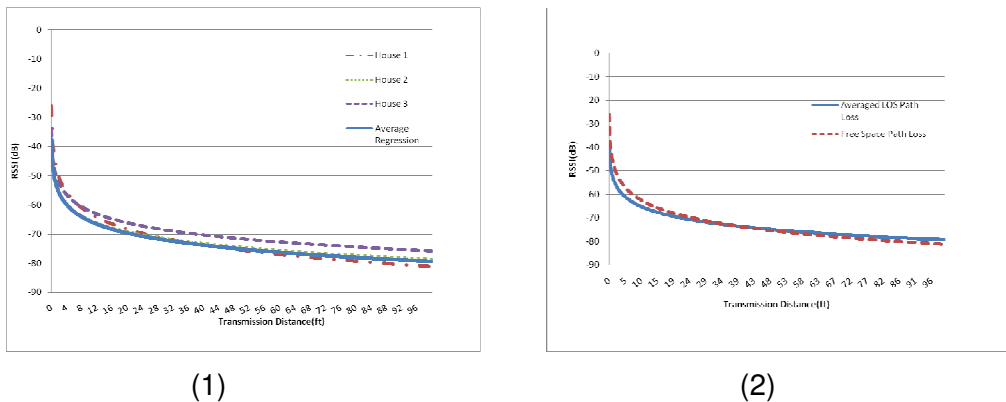


Figure 7. (1): Cumulative Regression Results within Open Space of Three Houses;  
(2):The Comparison between the Averaged Open Space Path Loss and Free Space Path Loss.

### ***Effects of Wall Separation on Signal Strength***

When the wall separation effect was tested, the transmitter and the receiver were placed on the same floor and floor-attenuation-factor (FAF) was not considered yet. Thus the model (equation 4) was modified to the following format (equation 9), where q represents the number

of walls that the wireless signals transmitted through and  $AF_w$  stands for wall attenuation factor. Three path loss regression equations for three houses were yielded from the experimental results (Table 2). The 95% confidence interval for  $AF_w$  and  $n$  were also given in Table 2.

$$PL(dB) = PL(d_0) + 10n \log_{10} \frac{d}{d_0} + qAF_w[dB] \quad (9)$$

Table 2. Summary of Regression Models for Path Loss due to Wall Separation in House 1, 2 and 3.

	Regression Equation	Range of $PL(d_0)$	Range of $AF_w$	Range of $n$
House 1	$PL(dB) = -55.5 - 0.85 q - 14.4 \log_{10}(d)$	(-56.16,-54.84)	(-1.1,-0.6)	(-14.89,-13.91)
House 2	$PL(dB) = -54.7 - 1.04 q - 11.7 \log_{10}(d)$	(-55.20,-54.20)	(-0.79,-1.29)	(-12.09,-11.31)
House 3	$PL(dB) = -48.3 - 3.51 q - 15.5 \log_{10}(d)$	(-49.02,-47.58)	(-3.75,-3.27)	(-16.13,-14.87)
Overall	$PL(dB) = -52.9 - 1.92 q - 13.7 \log_{10}(d)$	(-53.29,-52.51)	(-2.07,-1.77)	(-14.02,-13.38)

The overall regression model for path loss of wall separation was derived by combining three sets of data from three houses and conducting the analysis based on the linear relationship with wall separation and  $\log_{10}$  of transmission distance. Results yielded a  $PL(d_0)$  of -52.9 dB, an  $n$  of 1.37 and an  $AF_w$  of 1.92. Compared to the house LOS path loss model, the values of  $n$  were very close (1.37 for wall attenuation path loss model versus 1.4 for open space path loss model). However, 8.53 dB more path loss was found in the offset of wall attenuation model than open space path loss model (-52.9 dB for wall attenuation path loss model versus -44.37 dB for open space path loss model).

### Effects of Floor Separation on Signal Strength

When a transmitter and a receiver are located on different floors, it can be assumed that wireless signal first transmit through open space and walls of the same floor and then through floors vertically. The attenuation caused by floor is quantified by the FAF (floor attenuation factor), which is the function of the number of the floors. The overall path loss model is the sum of the wall separation based single floor path loss model (equation 9) and FAF. It is given by

$$PL(dB) = PL(d_0) + 10n \log_{10} \frac{d}{d_0} + qAF_w[dB] + FAF[dB] \quad (10)$$

In this work, FAF for the attenuation through one floor is derived by subtracting the predicted free space path loss at the floor transmission distance (8 feet) from the experimental floor path loss data. The path loss at 8 feet in the free space is -60.99 dB when equation 8 was applied. The mean and 95% confidential interval of FAF through one floor in three houses were shown in Table 3. Additional FAF when signal were transmitted through two floors were obtained by subtracting the path loss through one floor from that through two floors. The mean and 95% confidential interval of the additional FAF were also shown on Table 3. The overall

FAF was derived by combining three sets of data from three houses and conducting the analysis. Results yielded the FAF value of -19.59 dB for one floor separation and -5.84 dB for additional floor separation.

This coincides with the precious research result that FAF is about -15 dB for one floor separation and addition -6 dB to -10 dB for every additional floor separation (Panjwani et al., 1996).

Table 3. Summary of Path Loss due to Floor Separation in House 1, 2 and 3.

	FAF through 1 floor	95% CI	Additional FAF through 2 floors	95% CI
House 1	-21.26	(-22.183,-20.337)	-4.127	(-5.2771,-2.9769)
House 2	-16.06	(-16.637,-15.483)	-9.5667	(-10.1241,-9.0092)
House 3	-21.343	(-21.853,-20.834)	-3.9167	(-4.5464,-3.2870)
Overall	-19.592	(-20.129,-19.054)	-5.8415	(-6.4491,-5.2339)

### **Overall Path Loss Model**

After the FAF was added to the wall separation model, the overall path loss model was given by

$$PL(dB) = -52.9 - 1.92q - 13.7 \log_{10}(d) - \begin{cases} 0 & \text{same floor} \\ 19.59 & \text{one floor} \\ (19.59 + 5.84) & \text{two floors} \end{cases} \quad (11)$$

The variations of all the parameters were discussed in the table 2 and 3. Compared to the path loss model ( $PL(d_0) = -47$  dB and  $n=1.7$  for LOS) for 5GHz (Ghassemzadeh and Tarokh, 2003), 5.9 dB difference and 0.33 difference were found for the parameter of  $PL(d_0)$  and  $n$  separately. This was expectable since the  $PL(d_0)$  is due to the difference between the transmission frequencies (equation 2) and the value of  $n$  mainly corresponds to the effects of the transmission distance, which can explain the minor difference. The previous research showed that the FAF is about 15 dB for one floor separation and 6-10 dB for every additional floor (Panjwani et al., 1996; Andersen et al., 1995; Seidel and Rappaport, 1992). This coincides with finding of 19.59 dB for one floor separation and 5.84 dB for every additional floor as showed above .

### **Effects of 2.4GHz Devices on Signal Strength**

The statistical analysis of the RSSI measurements when all the devices were off and on was shown on Figure 8. It can be seen that two means were very close to each other (-84.887 dB versus -85.203 dB) while the 95% confidence interval for two means almost covered the same range ((-85.574 dB, -84.200 dB) versus (-85.684 dB, -84.722 dB)). The results of the two sample t-test showed that the 95% confidence interval of the difference between these two conditions was (-0.521, 1.154) and the P-value was 0.456, which indicated that the path loss in these two conditions were not significantly different between when 2.4GHz devices were off and on. In another word, these wireless devices did not impact the wireless transmission of ZigBee. However, the limitation of this test was that the number of wireless devices was much less than the potential number of wireless devices that could incur the serious signals traffic. Further

research was needed to study the RSSI performance of ZigBee when co-exist with large amount of wireless devices.

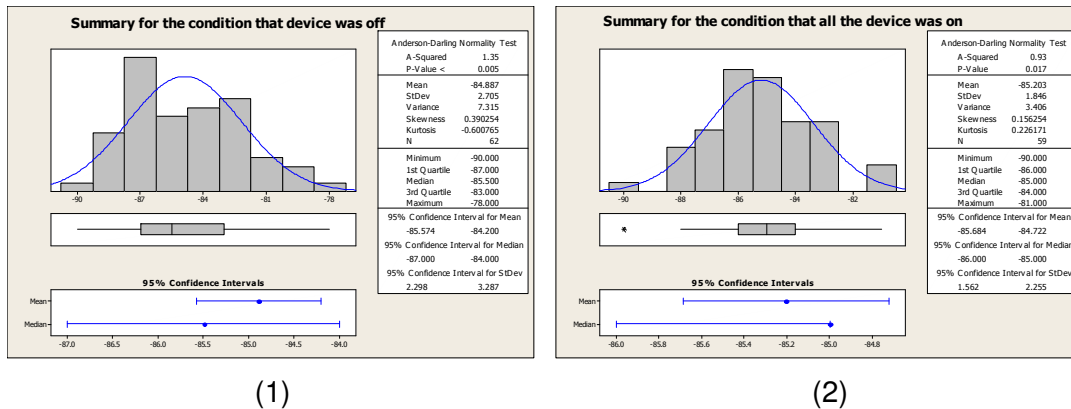


Figure 8. Statistical Summary of RSSI Measurements of the Transmission with All the Other 2.4GHz Devices Off (1) and On (2).

### Validation of the Predictive Models

To validate the models derived by the procedure discussed above, RSSI data were collected in another similar house, which was coded as house 4. Then errors between the predictive signal strength and the experimental data were plotted against the wall separation and the transmission distance (Figure 9). The errors of less than 16.3 dB were expectable due to the fact that the structure, the layout and furniture vary a lot from house to house and thus fast fading should differ (Seidel and Rappaport. 1992). The range of errors was from 0 dB to 22 dB, which was relatively wide. It indicated that at the transmission distance of 2.5 feet to 7.5 feet with 0 to 4 wall separation, the error was much higher than other transmission distances. At these distances, the experimental path loss was 15 to 22 dB different from the predicted values by the model. This could be explained by the radio energy boost that was caused by the radio scattering when wireless signal transmitted through the crowded furniture in the blue locations of house 4 as Figure 9 showed. While at the far transmission distances, the path loss was mainly caused by the multiple path error, it should be close to what was predicted by the model. It can be concluded that the model worked well to predict the path loss for the signal through walls when the transmission distance was greater than 10 feet.

For the factor of floor separation, the error between the experimental data and the predicted path loss data was analyzed. The errors for the path loss through one floor and two floors were found to be 9.76 dB and 1.5 dB separately. This result was acceptable since the errors fell within the range of less than 16.3 dB.

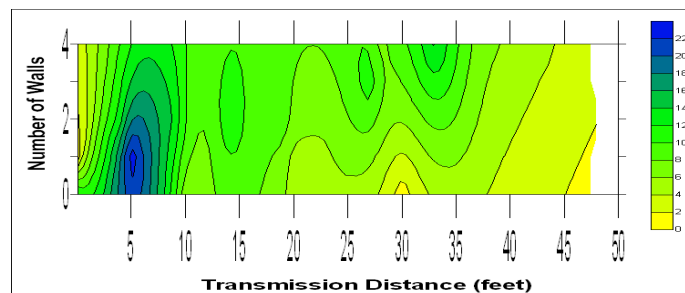


Figure 9. Contour Plot of Errors between House 4 Wall Separation Path Loss and Predicted Path Loss Based on Predicted Model.



## Conclusion

The results of this work provided the prediction models of path loss for the emerging ZigBee wireless protocol in residential house environment. The application of this work will lead to improve the signal transmission of wireless sensor networks for HVAC control in residential environment. The parameters of the developed models were found by conducting the experiments and statistical analysis. The path loss of LOS inside a house was found to act similarly to that in open-air environment. The R-Sq value of 73.6% for wall separation model was expectable for the derived models given the diversity of the layout and structure of rooms and furniture. The impact of other ISM 2.4GHz wireless devices on ZigBee transmission was tested and it indicated that they did interfere with ZigBee. The comparison of the predicted models to the measured data showed that the errors were mostly less than 10 dB, which was acceptable because of the variation. This indicated that the models worked well to predict the path loss.

However, the experiments were conducted in only four typical residential houses. In reality, there are much more types of residential houses and their layouts vary a lot. Therefore, it might cause high errors if the model is applied to the residential houses that are much different from the test houses. Future work is needed to test more houses to reduce the modeling error. Moreover, the emerging new materials of residential houses might induce more or less path loss, which is unknown. Therefore, more work is also needed to reveal the impact of new materials on path loss.

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